Spectroscopy Using Quantum Logic

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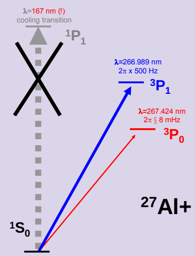
Overview

Fundamental steps for precision spectroscopy in an ion trap:

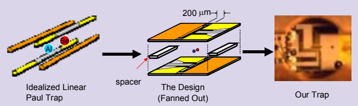
Cool → Initialize → Probe → Detect

- Traditionally, all steps are performed on the ion under study, however, not all ions have accessible transitions that can be used for each step.
- **Problem:** Perform spectroscopy without a local transition for cooling or detection
- **Idea:** Put a second ion in the same trap to aid in cooling, initialization and detection through the use of coherent population transfer
- **Sympathetic Cooling** can reach ground state of collective motion[1]
- **State Initialization** can be made directional, deterministic and fast employing a second ion
- **Detection** can be achieved by transferring information from the spectroscopy ion to the logic ion[2]
- In our application, we use this technique to operate an $^{27}Al^+$ ion as an optical frequency standard



1. Barrett M.D. et. al., Phys. Rev. A 68 (4) 2003.
2. Wineland D.J. et. al., *Proceedings of 6th Symposium on Frequency Standards and Metrology*, P. Gill, ed (World Scientific, Singapore, 2002) pp. 361-368

The Trap



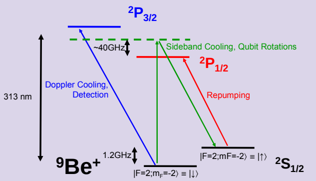
- Single-zone, microfabricated, linear, Paul trap
- Typical Operating Parameters:

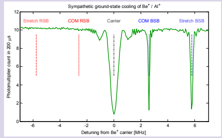
RF Frequency	103 MHz
COM Frequency	2.62 MHz
Radial Frequencies	13-15 MHz
Inter-ion Spacing	~4μm
Vacuum Pressure	~10^{-11} Torr

Trap by Volker Meyer

Sympathetic Cooling

- "Spectroscopy" ion ($^{27}Al^+$) can be brought to ground state by laser cooling "logic" ion ($^9Be^+$).
- Trap ions and reach ‹n› < 10 by Doppler cooling in a direction with components along all eigenmodes of motion
- Six modes of motion to cool for two ions in 3-D
- Cool to ground state for axial modes using Raman sideband pulses on Be+
- Compensate for poor coupling of Be+ to radial modes using an additional, radial electric field to momentarily tilt the ion crystal

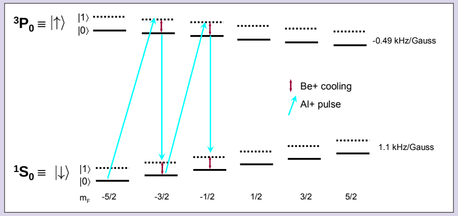




Ground State Spectrum on Be+

Deterministic Preparation

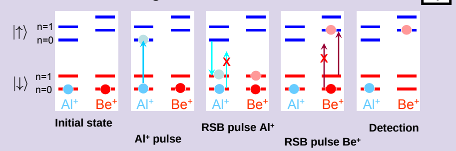
- Cannot rely on spontaneous emission to optically pump Al+
- Beginning in motional ground state, perform sequence of sideband pulses followed by cooling on Be+
- Features:
1) **Directional.** Sideband pulses from ground state between two levels only drive one direction.
2) **Deterministic.** Switching role of spontaneous emission to Be+ makes process purely deterministic for Al+

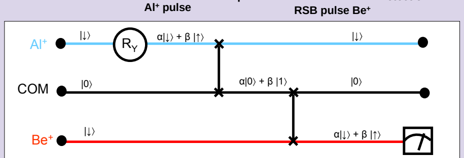


Example of scheme for deterministically preparing ion in m_F = -1/2

State Detection

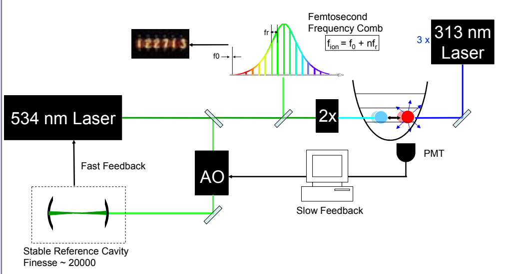
- $^1S_0 \rightarrow {}^1P_1$ Detection transition in Al+ is inaccessible
- Beginning in ground state of motion, transfer information from Al+ internal state to motional state then to Be+ internal state using red sideband pulses (RSB)
- In the special case that one qubit is in the ground state, the transfer pulses implement a SWAP gate.
- State detected using resonant flourescence on Be+





Schematic and circuit diagrams for state transfer

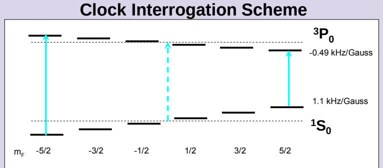
3P0 as a Frequency Standard



Laser Stabilization and Frequency Measurement Scheme

- Optical atomic clocks have the potential to improve accuracy and stability of frequency standards
- Al^+ $^1S_0 \rightarrow {}^3P_0$ has several favorable qualities for use as a clock (extremely small blackbody shift, negligible electric quadrupole shift, and small AC stark shift)

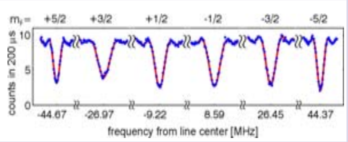
Clock Interrogation Scheme



Average of two stretched states gives a first-order B-field independent frequency

Results

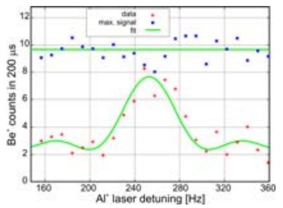
- Deterministic state preparation has been achieved and demonstrated on $^3P_1$ Zeeman levels[3]



Demonstration of State Preparation

3. P.O. Schmidt *et al.*, *Science*, 309, 749 (2005)

- Found $^3P_0$ transition and performed Rabi spectroscopy with a minimum Fourier-limited linewidth of 40 Hz
- Evaluated a number of systematics related to the absolute frequency measurement of the $^3P_0$ transition
- Routinely achieve ~50% contrast on $^3P_0$. Currently believed to be limited by laser phase noise due to table vibrations, air currents or acoustic noise.

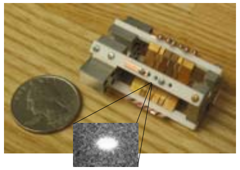


Observation of $^3P_0$ line

Outlook

Immediate Goals
- Improve frequency comparison with Hg+
- Finish evaluating relevant systematics

New Apparatus !
- New Trap: Symmetric Linear RF trap design.
  - No insulating surfaces near ions
  - Individual DC voltage control of each electrode
  - Axial probing possible
- Additional laser for $^1S_0 \rightarrow {}^3P_1$
  - Better preparation, better state transfer – better contrast?
- Trap doppler cancellation, new reference cavities – longer probe times?



New Trap and its First Ions

Long-term Objectives
- Test temporal variation of fundamental constants
- Entangled clock for better stability

Preliminary Error Budget

Effect	Shift [x 10^{-17}]	Uncertainty [x 10^{-17}]
Blackbody shift (T=300K)	1.2	0.5
Micromotion 2nd order Doppler	2	1
Micromotion 2nd order Doppler	8	8
Secular 2nd order Doppler	4	2
2nd order Zeeman	83	0.3
Be+ cooling laser Stark shift	3	3
AOM phase chirp	1	1
Background gas collisions	0	0.4
Total	99.2	8.8